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PRECISE PREDICTIONS FOR W-PAIR PRODUCTION AT LEP2 WITH RacoonWW [†]

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RacoonWW is the first Monte Carlo generator for $e^+e^- \to WW \to 4f(+\gamma)$ that includes the electroweak $\mathcal{O}(\alpha)$ radiative corrections in the double-pole approximation completely. Some numerical results for LEP2 energies are discussed, and the predictions for the total W-pair cross section are confronted with LEP2 data.

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RacoonWW is the first Monte Carlo generator for $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f(+\gamma)$ that includes the electroweak $\mathcal{O}(\alpha)$ radiative corrections in the double-pole approximation completely. Some numerical results for LEP2 energies are discussed, and the predictions for the total W-pair cross section are confronted with LEP2 data.

1 W-pair production at LEP2

The investigation of W-pair production at LEP2 plays an important role in the verification of the Electroweak Standard Model (SM). Apart from the direct observation of the triple-gauge-boson couplings in $\mathrm{e^+e^-} \to \mathrm{W^+W^-}$, the increasing accuracy in the W-pair-production cross-section and W-mass measurements has put this process into the row of SM precision tests.

To account for the high experimental accuracy [1,2], on the theoretical side is a great challenge: the W bosons have to be treated as resonances in the full four-fermion processes $\mathrm{e^+e^-} \to 4f$, and radiative corrections need to be included. While several lowest-order predictions are based on the full set of Feynman diagrams, only very few calculations include radiative corrections beyond the level of universal effects (see Refs. 3,4 and references therein). Fortunately, to match the experimental precision for W-pair production at LEP2 a full one-loop calculation for the four-fermion processes is not needed, and it is sufficient to take into account only those radiative corrections that are enhanced by two resonant W bosons. A naive estimate of the neglected corrections yields $(\alpha/\pi)(\Gamma_\mathrm{W}/M_\mathrm{W}) \sim 0.5\%$. The theoretically clean way to carry out this approximation is the expansion about the two resonance poles, which is called *double-pole approximation* (DPA) [5]. A full description of this strategy and of different variants used in the literature [6,7,8] (some of them involving further approximations) is beyond the scope of this article. We can only briefly sketch the approach pursued in RacoonWW [9,10].

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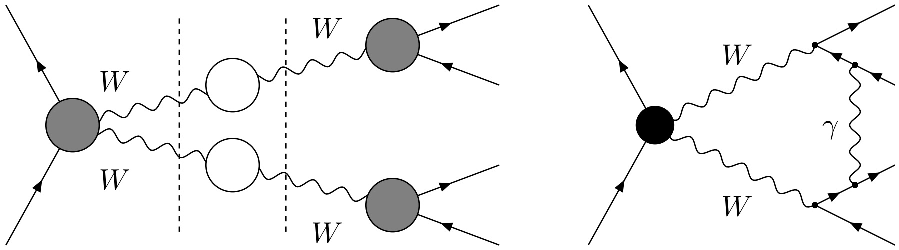

Figure 1: Structure of virtual factorizable corrections (l.h.s.), with loop corrections in the blobs, and a typical diagram for virtual non-factorizable corrections (r.h.s.)

2 Radiative corrections with RacoonWW

In DPA, $\mathcal{O}(\alpha)$ corrections to $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$ can be classified into two types: factorizable and non-factorizable corrections. We first focus on virtual corrections.

Factorizable corrections are those that correspond either to W-pair production or to W decay. Virtual factorizable corrections are represented by the schematic diagram on the l.h.s. of Fig. 1, in which the shaded blobs contain all one-loop corrections to the on-shell production and on-shell decay processes, and the open blobs include the corrections to the W propagators. For the corresponding matrix element $\mathcal{M}$ the application of the DPA amounts to the replacement

$$\mathcal{M} = \frac{R(k_{\mathrm{W}^+}^2, k_{\mathrm{W}^-}^2)}{(k_{\mathrm{W}^+}^2 - M_{\mathrm{W}}^2)(k_{\mathrm{W}^-}^2 - M_{\mathrm{W}}^2)} \;\to\; \frac{R(M_{\mathrm{W}}^2, M_{\mathrm{W}}^2)}{(k_{\mathrm{W}^+}^2 - M_{\mathrm{W}}^2 + \mathrm{i}M_{\mathrm{W}}\Gamma_{\mathrm{W}})(k_{\mathrm{W}^-}^2 - M_{\mathrm{W}}^2 + \mathrm{i}M_{\mathrm{W}}\Gamma_{\mathrm{W}})}, \quad (1)$$

where the originally gauge-dependent numerator $R(k_{\mathrm{W}^+}^2, k_{\mathrm{W}^-}^2)$ is replaced by the gauge-independent residue $R(M_{\mathrm{W}}^2, M_{\mathrm{W}}^2)$. The one-loop corrections to this residue can be deduced from the known results for the pair production and the decay of on-shell W bosons. However, the spin correlations between the two W decays should be taken into account.

Non-factorizable corrections [11] comprise all those doubly-resonant corrections that are not yet contained in the factorizable ones, and include, in particular, all diagrams involving particle exchange between the subprocesses. Such diagrams only lead to doubly-resonant contributions if the exchanged particle is a photon with energy $E_\gamma \lesssim \Gamma_{\mathrm{W}}$; all other non-factorizable diagrams are negligible in DPA. A typical diagram for a virtual non-factorizable correction is shown on the r.h.s. in Fig. 1, where the full blob represents tree-level subgraphs. We note that diagrams involving photon exchange between the W bosons contribute both to factorizable and non-factorizable corrections; otherwise the splitting into those parts would not be gauge-invariant.

In RacoonWW the virtual corrections are treated in DPA, including the full set of factorizable and non-factorizable $\mathcal{O}(\alpha)$ corrections. The real corrections are calculated from full matrix elements for $\mathrm{e^+e^-} \to 4f\gamma$, as described in Ref. 12, i.e. the DPA is not used in this part. In this way, we avoid potential problems in the definition of the DPA for the emission of photons with energies $E_\gamma \sim \Gamma_{\mathrm{W}}$. On the other hand, this asymmetry in the calculation of virtual and real corrections requires particular care concerning the structure of IR and mass singularities. The singularities have the form of a universal radiator function convoluted with the respective lowest-order matrix element squared $|\mathcal{M}_0|^2$ of the non-radiative process. Since the virtual corrections are calculated in DPA, but the full matrix element is used for the real photons, a simple summation of virtual and real corrections would lead to a mismatch in the singularity structure and eventually to totally wrong results. Therefore, we extract those singular parts from the real photon contribution that exactly match the singular parts of the virtual photon contribution, then replace in these terms the full $|\mathcal{M}_0|^2$ by the one calculated in DPA, and finally add this modified part to the virtual corrections. This modification is allowed within DPA and leads to a proper matching of all IR and mass singularities. This treatment has been carried out in two different ways, once following phase-space slicing, once using the subtraction formalism of Ref. 13.

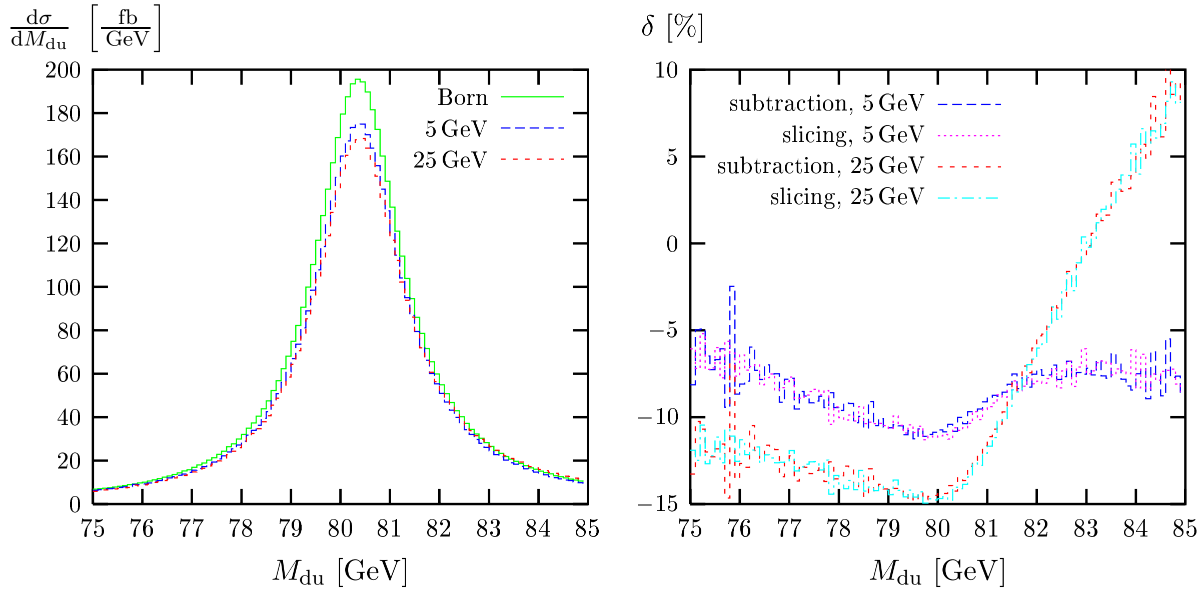

Figure 2: Invariant-mass distribution of the $d\bar{u}$ pair for $e^+e^- \to \nu_\mu \mu^+ d\bar{u}$ and $\sqrt{s} = 200\,\mathrm{GeV}$ (taken from Ref. 9a)

Beyond $\mathcal{O}(\alpha)$, RacoonWW includes soft-photon exponentiation and leading higher-order ISR effects in the structure-function approach. Using G_μ as input parameter instead of $\alpha(0)$, also the leading effects from $\Delta\alpha$ and $\Delta\rho$ are absorbed and partially resummed in the lowest order.

3 Phenomenological results

A survey of numerical results obtained with RacoonWW has already been presented in Ref. 9 for LEP2 and linear-collider energies. Here we only review the W invariant-mass distribution given there and extend the results for the total cross section.

Figure 2 (l.h.s.) shows the invariant-mass distribution of the $d\bar{u}$ quark pair for the semi-leptonic channel $e^+e^- \to \nu_\mu \mu^+ d\bar{u}$ at $\sqrt{s} = 200\,\mathrm{GeV}$ at tree-level and with electroweak $\mathcal{O}(\alpha)$ corrections for two different recombination cuts, $M_{\mathrm{rec}} = 5$ and $25\,\mathrm{GeV}$. The recombination of photons with final-state charged fermions is performed as described in Ref. 9: we first determine the lowest invariant mass $M_{\gamma f}$ built by an emitted photon and a charged final-state fermion. If $M_{\gamma f}$ is smaller than M_{rec}, the photon momentum is added to the one of the corresponding fermion f. The maxima of the corrected line shapes differ by up to 30–40 MeV for the two values of M_{rec}. As expected, there is a tendency to shift the maxima to larger invariant masses if more and more photons are recombined. In Fig. 2 (r.h.s.) we display the relative corrections $\delta = d\sigma/d\sigma_0 - 1$ for the two values of M_{rec}, which illustrates the strong dependence of the corrected invariant-mass distributions on the treatment of the real photons. We obtain consistent results for the phase-space "slicing" and the "subtraction" methods. The size of the shown effects demonstrates that a careful treatment of real photons is mandatory in the W-mass reconstruction at LEP2 accuracy.

Figure 3 shows a comparison of RacoonWW results and of other predictions with recent LEP2 data, as given by the LEP Electroweak Working Group [1,14]. The data are in good agreement with the predictions of RacoonWW and YFSWW3 [6]. The predictions of these two generators differ between 0.5–0.7%.[§] More details on the conceptual differences of the two generators, as well as a detailed comparison of numerical results, can be found in Ref. 4. Figure 3 also includes the prediction provided by GENTLE [15], which differs from the RacoonWW and YFSWW3 results by 2–2.5%. This difference is due to the neglect of non-leading, non-

[§]Meanwhile the dominant source of this difference has been found, and the new results of YFSWW3 are closer to the results of RacoonWW. Details on the new YFSWW3 predictions can be found in Ref. 4.

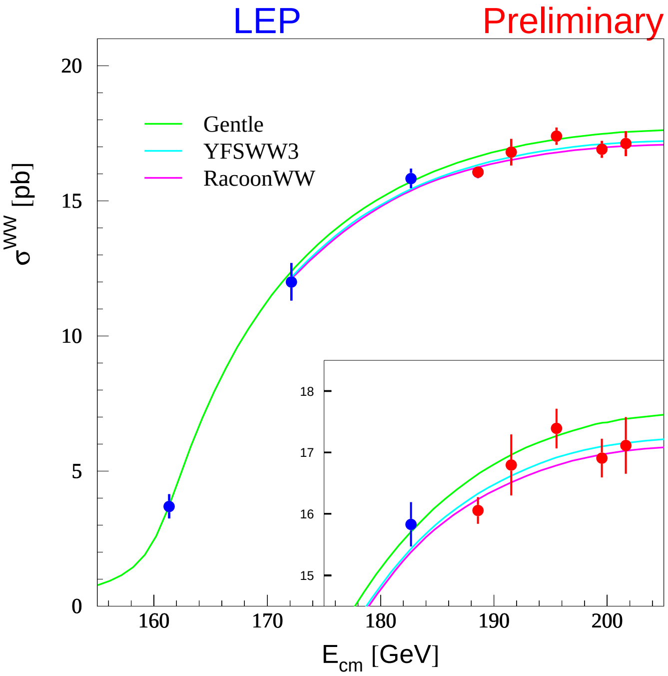

Figure 3: Total WW production cross section at LEP2, as given by the LEPEWWG [14]

universal $\mathcal{O}(\alpha)$ corrections in GENTLE. In summary, the comparison between SM predictions with the precise measurements of the W-pair production cross section at LEP2 reveals evidence of non-leading electroweak radiative corrections beyond the level of universal effects.

References

1. C. Sbarra, these proceedings.
2. A. Straessner, these proceedings.
3. W. Beenakker et al., in *Physics at LEP2* (Report CERN 96-01, Geneva, 1996), G. Altarelli, T. Sjöstrand and F. Zwirner (eds.), Vol. 1, p. 79, hep-ph/9602351.
4. *Four-Fermion Working Group Report* of the *LEP2 Monte Carlo Workshop*, CERN, 1999/2000, in preparation.
5. R.G. Stuart, *Phys. Lett.* **B262** (1991) 113;
   A. Aeppli, G.J. van Oldenborgh and D. Wyler, *Nucl. Phys.* **B428** (1994) 126.
6. S. Jadach et al., *Phys. Lett.* **B417** (1998) 326; hep-ph/9907436.
7. W. Beenakker, F.A. Berends and A.P. Chapovsky, *Nucl. Phys.* **B548** (1999) 3.
8. Y. Kurihara, M. Kuroda and D. Schildknecht, *Nucl. Phys.* **B565** (2000) 49.
9. A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, *Phys. Lett.* **B475** (2000) 127; *EPJdirect* **C4** (2000) 1 (hep-ph/9912447).
10. A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, BI-TP 2000/06, in preparation.
11. W. Beenakker, F.A. Berends and A.P. Chapovsky, *Phys. Lett.* **B411** (1997) 203 and *Nucl. Phys.* **B508** (1997) 17;
    A. Denner, S. Dittmaier and M. Roth, *Nucl. Phys.* **B519** (1998) 39 and *Phys. Lett.* **B429** (1998) 145.
12. A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, *Nucl. Phys.* **B560** (1999) 33.
13. S. Dittmaier, *Nucl. Phys.* **B565** (2000) 69;
    M. Roth, dissertation ETH Zürich No. 13363, 1999.
14. http://lepewwg.web.cern.ch/LEPEWWG/.
15. D. Bardin, M. Bilenky, A. Olchevski and T. Riemann, *Phys. Lett.* **B308** (1993) 403;
    D. Bardin et al., *Comput. Phys. Commun.* **104** (1997) 161.